Progress Report

Frequency and Angular Dependence of Low Frequency East China Sea Bottom Scattering Strengths

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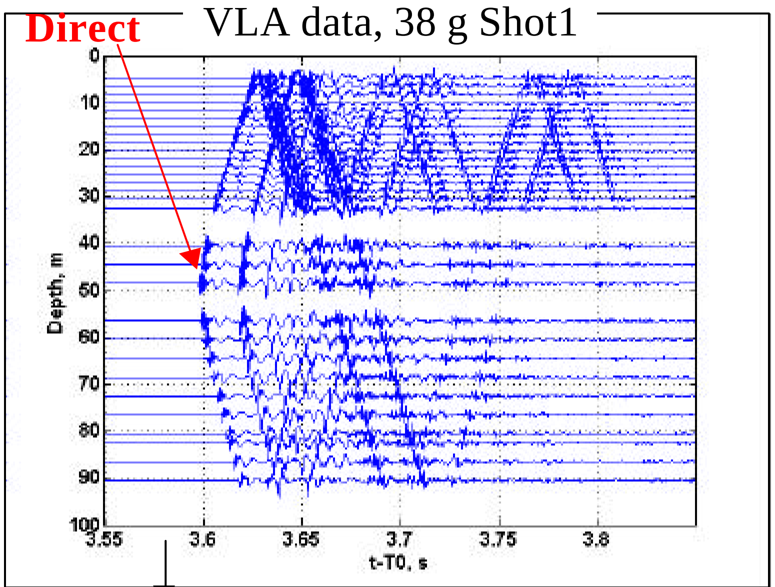
Scattering Strength Extraction

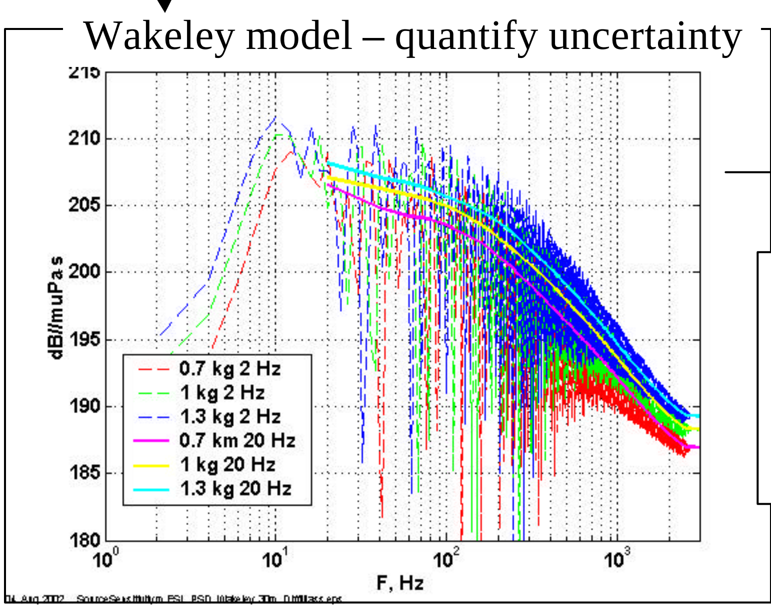
- $SS = RL(t) + TL(t) - ESL - 10\log10(\pi CR(t))$
  - SS is empirical scattering strength.
  - RL is time-dependent received level.
  - TL is time-dependent two-way transmission loss.
  - ESL is energy source level.
  - $\pi CR(t) \sim A(t)$ - insonified area, R(t) is range, and omnidirectional source is assumed.
- Above, terms explicitly dependent on time are highlighted with red color.
- For range-independent environments, $SS=SS(\Theta_{inc},\Theta_{scat})$, and not SS(t).
- Initial approach:
  - Use TL as modeled by ARL/UT based on
    - Inversion of environmental properties based on measured 38 g shots propagation.
    - Forward propagation modeling
  - Use use Wakeley model for ESL of the explosive 1 kg source.
  - Use RL as recorded by VLA:
    - Individual sensor for angle-aggregate SS.
    - Beamform to extract angular dependence.
- Turns out, we have problems with source model.
- Adjust approach:
  - Do the best possible under circumstances estimate of the SS.
  - Characterize uncertainty in SS resulting from uncertainty in source and TL.

Source Function Sensitivity to Weight Uncertainty

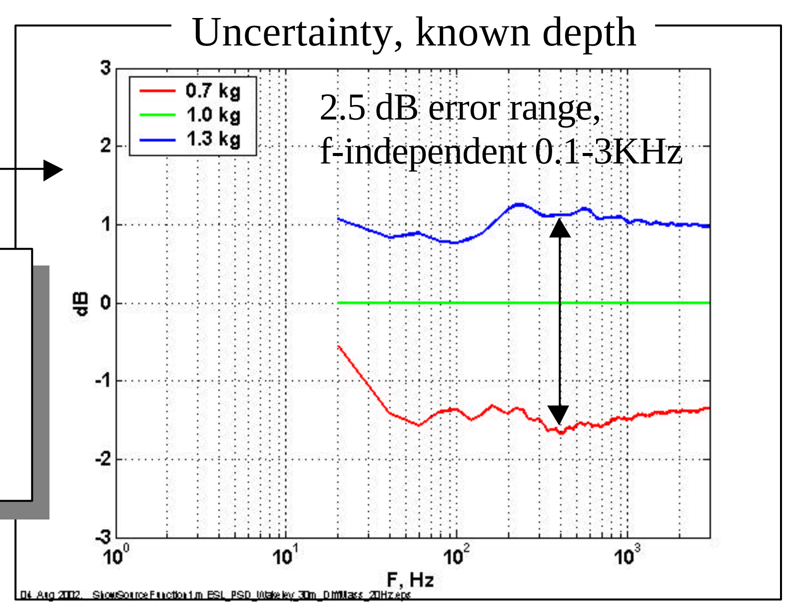


- Source PSD depends on WBS depth/mass.
- Depth can be inferred from direct arrival structure.
- If available, pulse separation gives estimate of weight.
- If can not resolve, assume some spread of weight, estimate uncertainty in energy density spectrum level (EDSL).
- Bottom right: EDSL uncertainty for 30% weight spread.

Estimate depth → Wakeley model – estimate weight

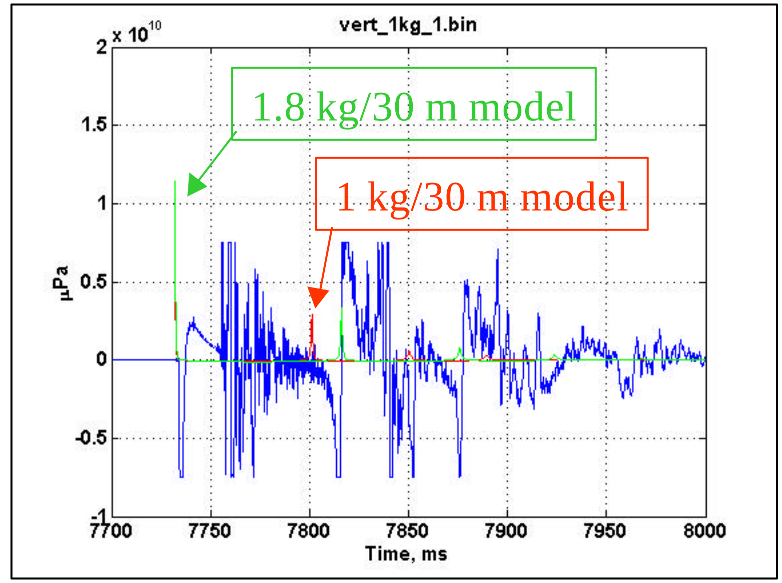


For 30% weight uncertainty, source level uncertainty is less than 2.5 dB.



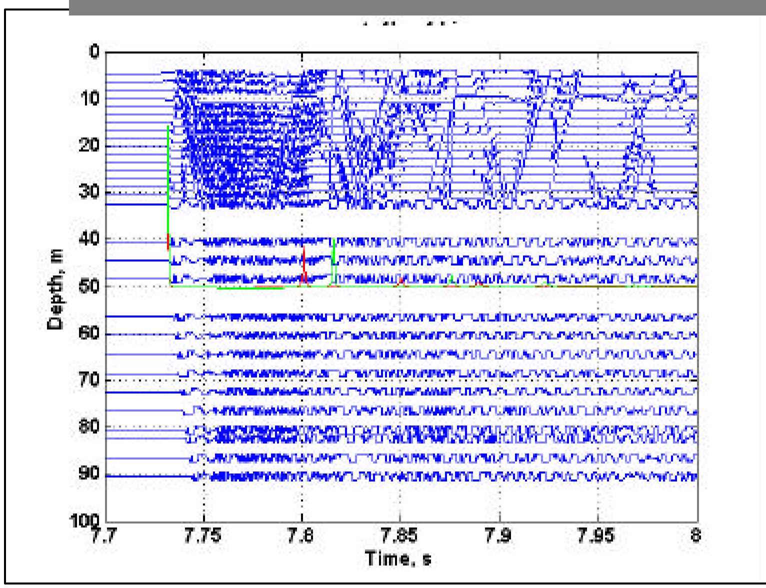
1 kg Shot, Direct Arrival on VLA and Desensitized Phone

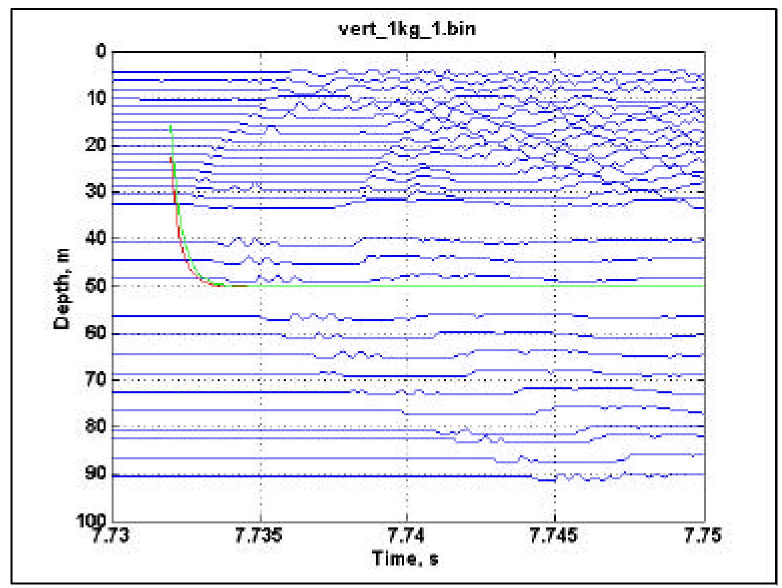
- For reference, model results are shown for 1 kg (red) and 1.8 kg (green) source at 30 m depth.
- Top: desensitized phone data.
- Bottom: direct arrival structure.
  - About 30 m detonation depth.
  - Individual arrivals are hard to identify.
- Features in overloaded direct arrival vaguely hint at 1.8 kg/30 m source. But 1.8 kg actual weight is unlikely for 1 kg nominal charge.



Can infer depth but not weight.

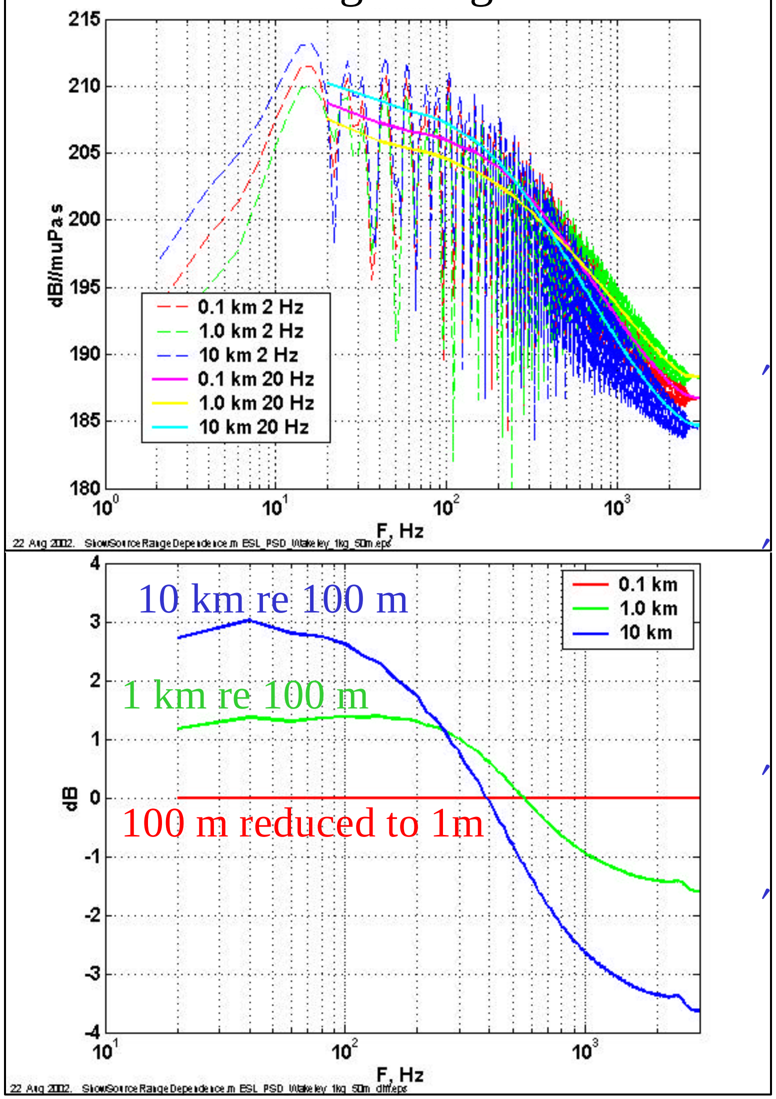
Use nominal weight, quantify error.





Range Dependence in Source Function

1 kg Charge



Wakeley model to compute source function for 38 g and 1 kg source at 50 m depth at range of 100 m, 1 km, and 10 km.

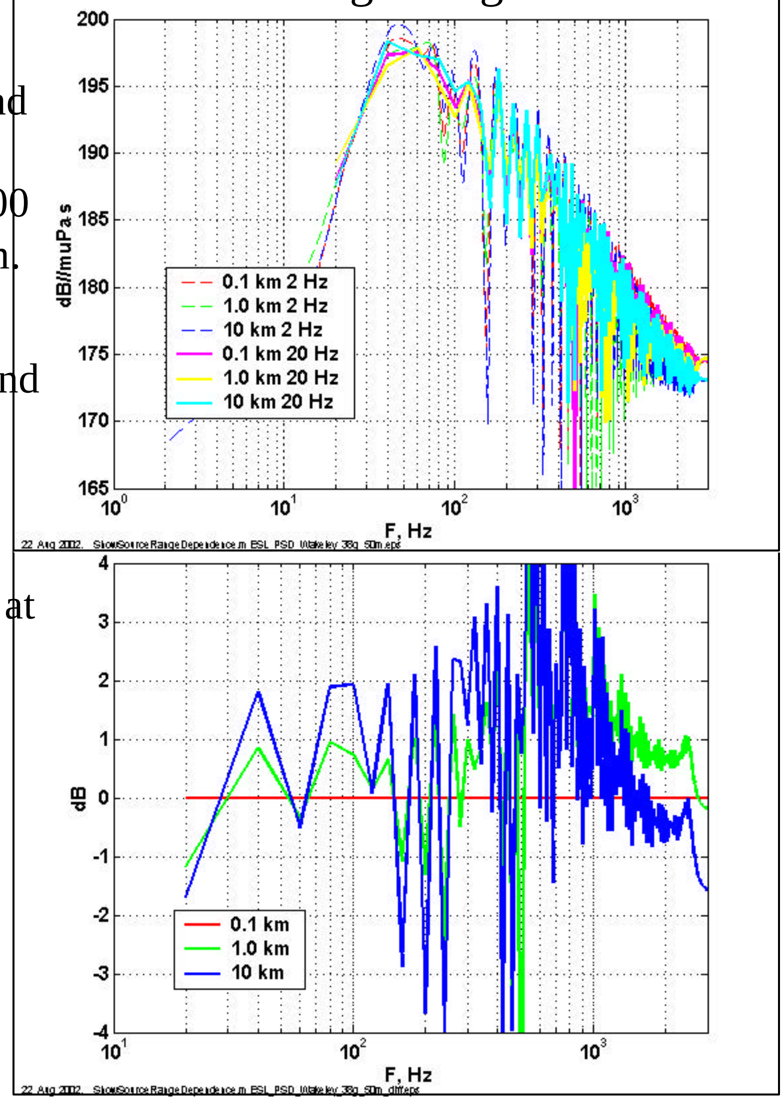
Top: EDSL, 2 Hz and 20 Hz resolution.

Bottom: EDSL deviation from that at 100 m.

Left: 1 kg charge.

Right: 38 g charge.

38 g Charge

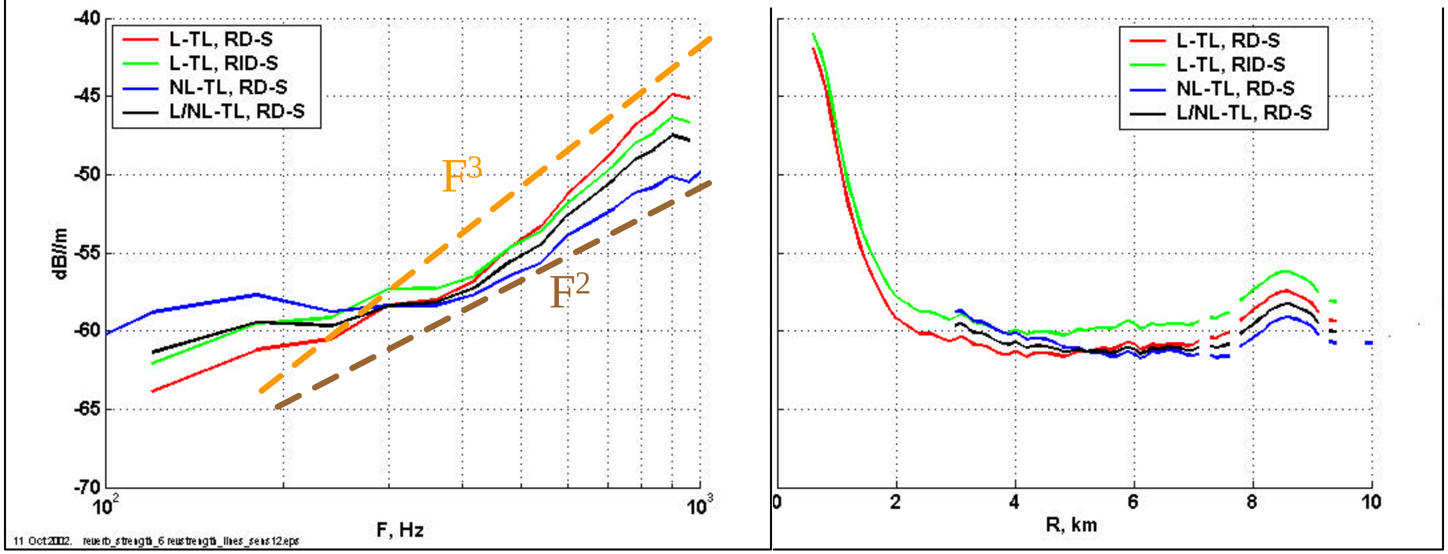


With 1 kg charge, observe f-dependence with range.

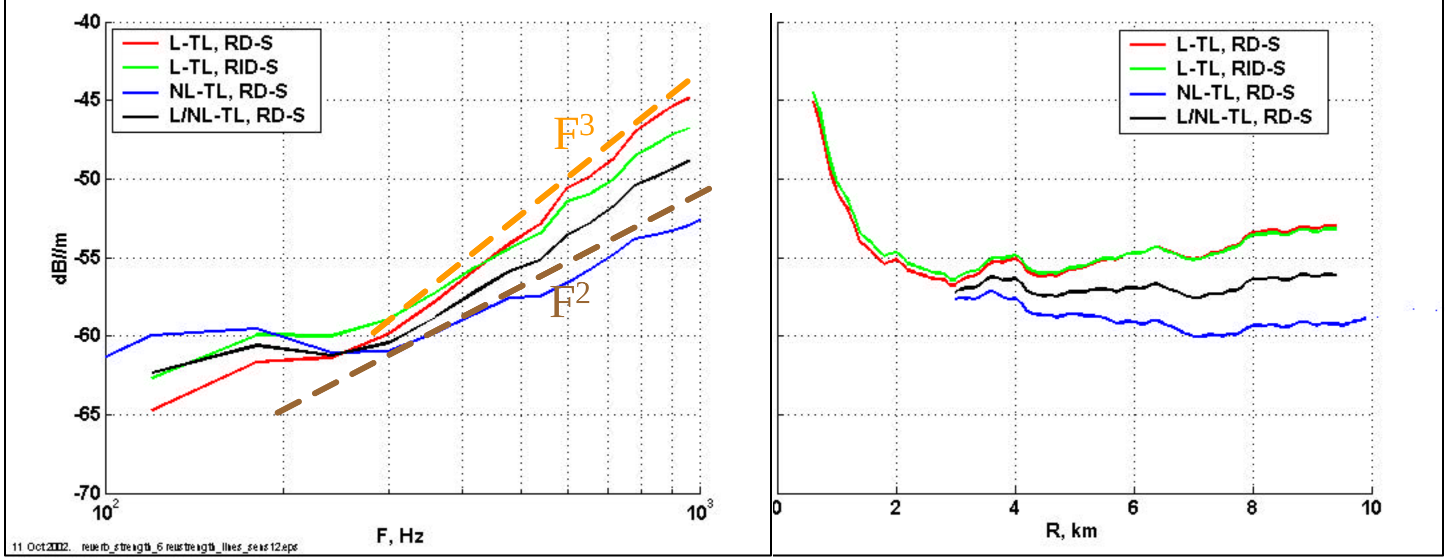
True feature of nonlinear source or Wakeley model artifact? Implications on SS?

Single Sensor SS, Mid-Water Sensor – 45 m

At 3 km

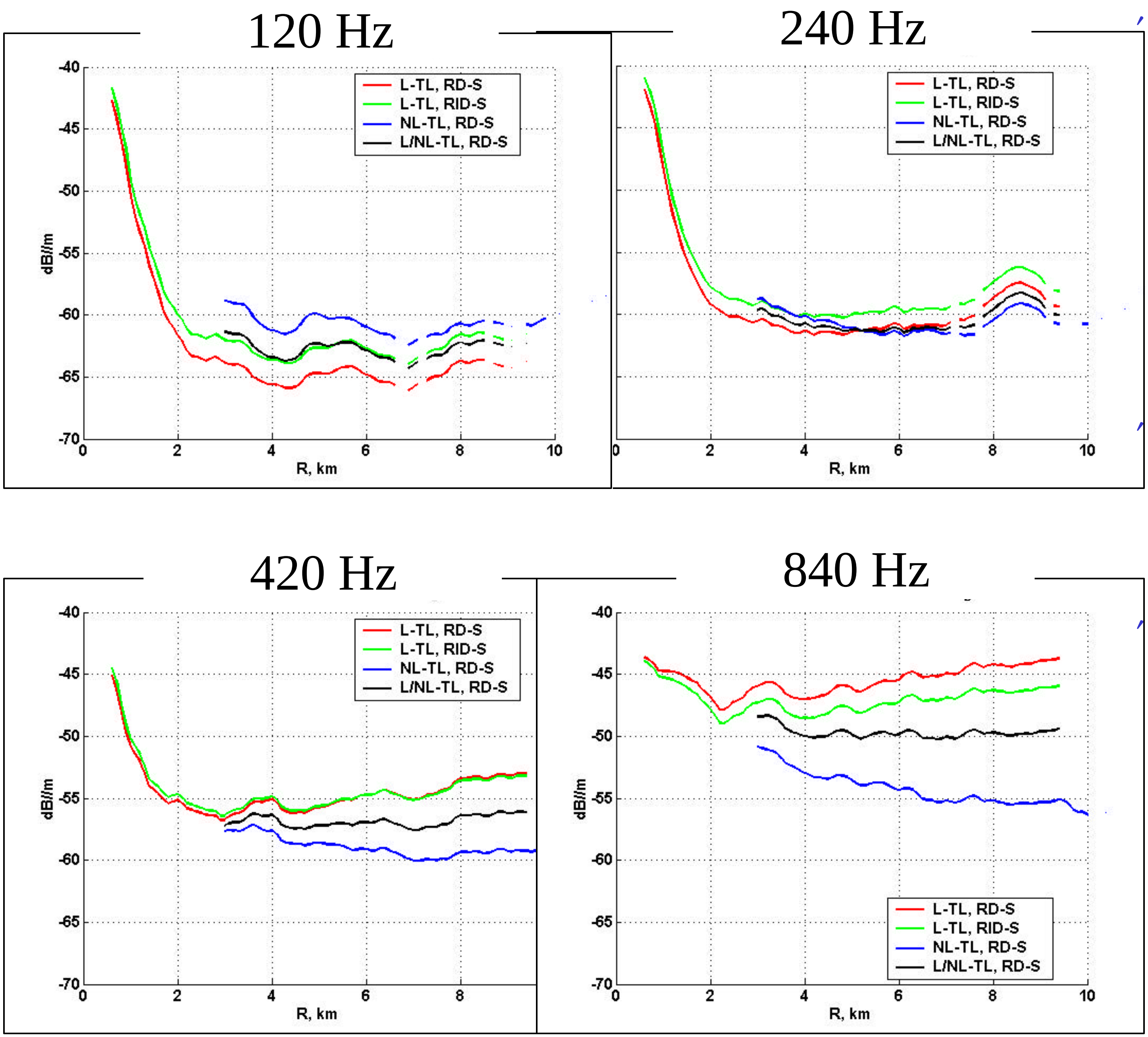


At 5 km



- Linear TL model:
  - F^3 dependence.
  - SS increasing with range for 420 Hz.
- Non-linear TL:
  - F^2 dependence.
  - SS decreases with R for 420.
- L/NL
  - In between: $F^{2.5}$.
  - R-independent.
- Different TL models:
  - dB-difference not huge, but predict different F-dependence.
  - Which F-dependence is right?

Single Sensor SS: Range Dependence, Mid-Water – 44 m



Linear TL:

- SS in dependent of range for 120, 240 Hz.
- SS increasing with range for 420, 840 Hz.
- Increases more for 840 Hz.

L/NL TL:

- SS independent of range.

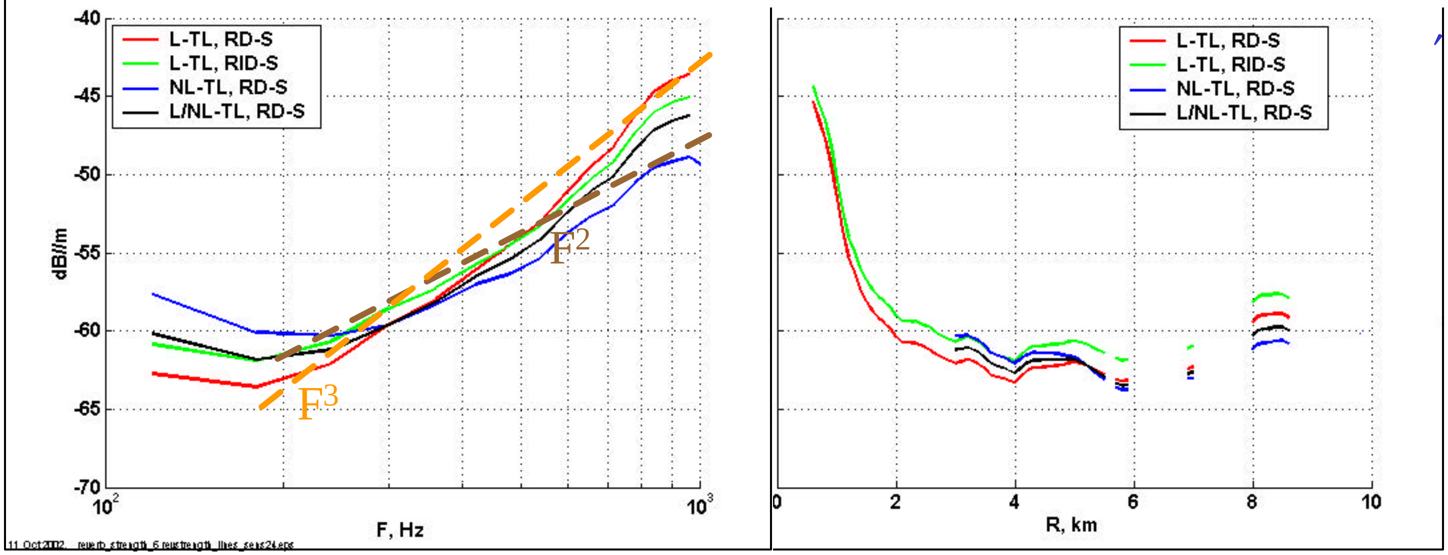
Is it an accidental fit, or do we really need to consider NL effects?

Question

- Assuming non-linear source, can “straighten” range-dependence of SS.
- Does this mean that we should account for source nonlinearity?
- May be, but may be not, as there are potential mechanisms for range dependence of the SS:
  - Range-dependence of environment
  - Scattering into different angles (coupling between modes) increasingly important with range

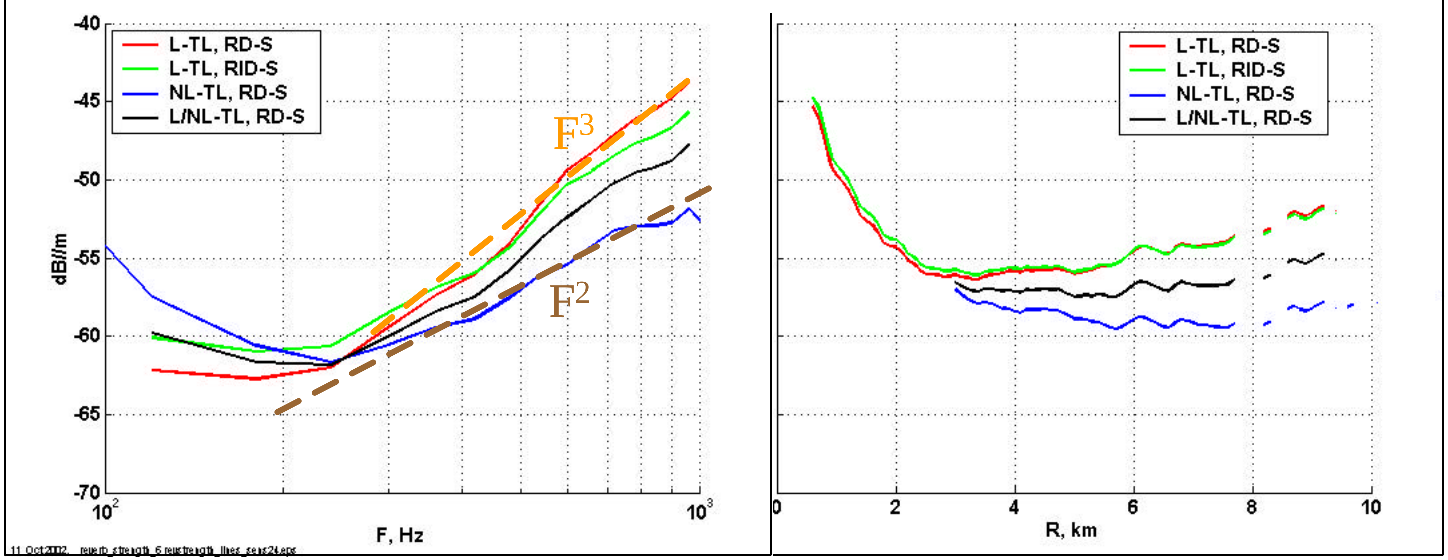
Single Sensor SS, Shallow Sensor – 15 m

At 3 km



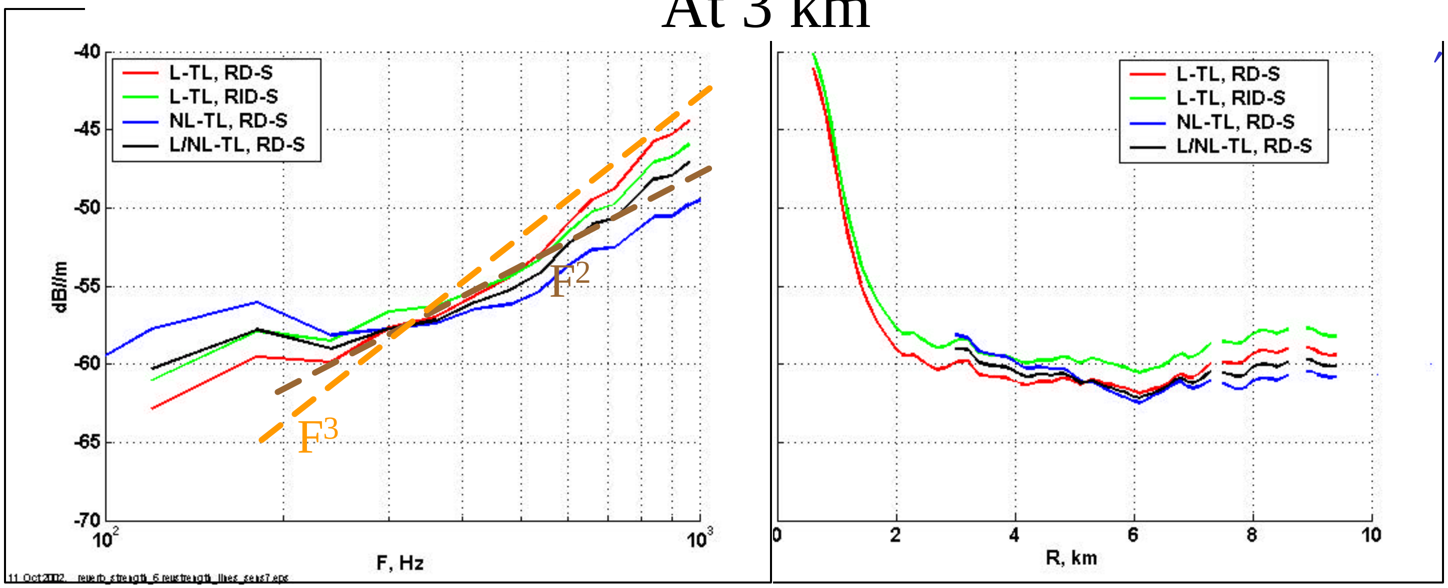
Results very similar to mid-water sensor

At 5 km



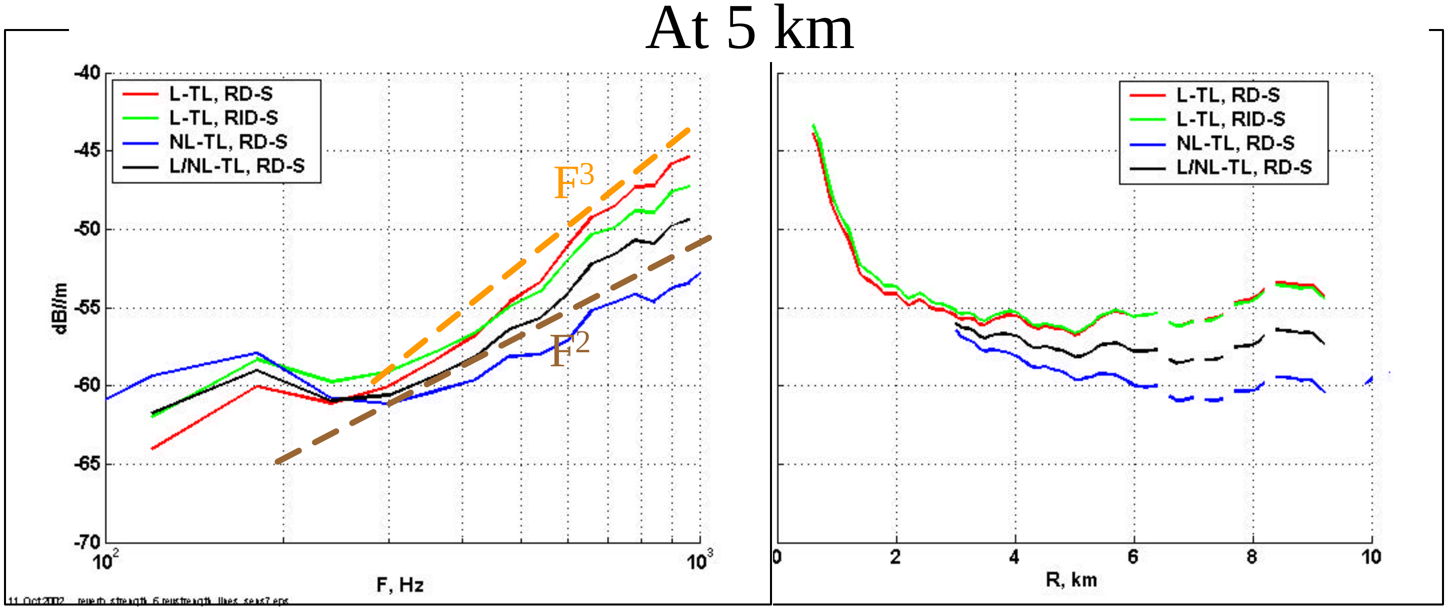
Single Sensor SS, Deep Sensor – 70 m

At 3 km



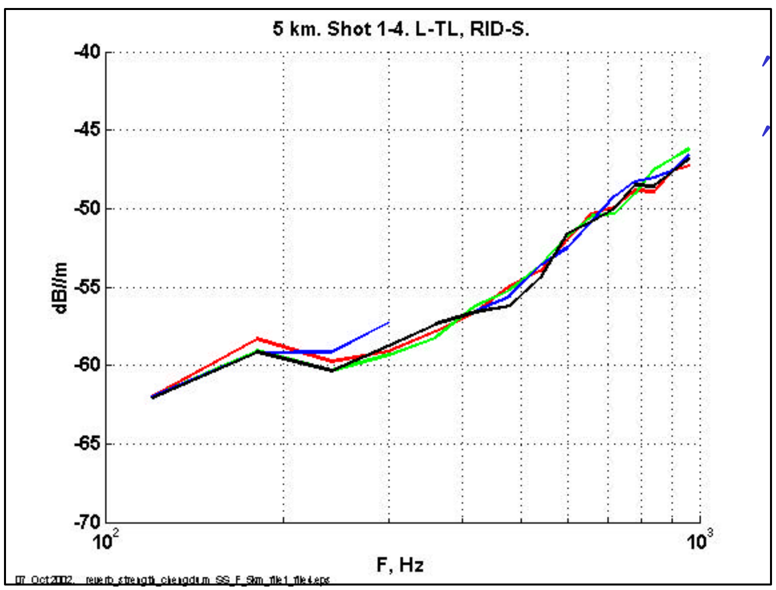
Results very similar to mid-water and shallow sensors.

At 5 km



Uncertainty in SS Estimate?

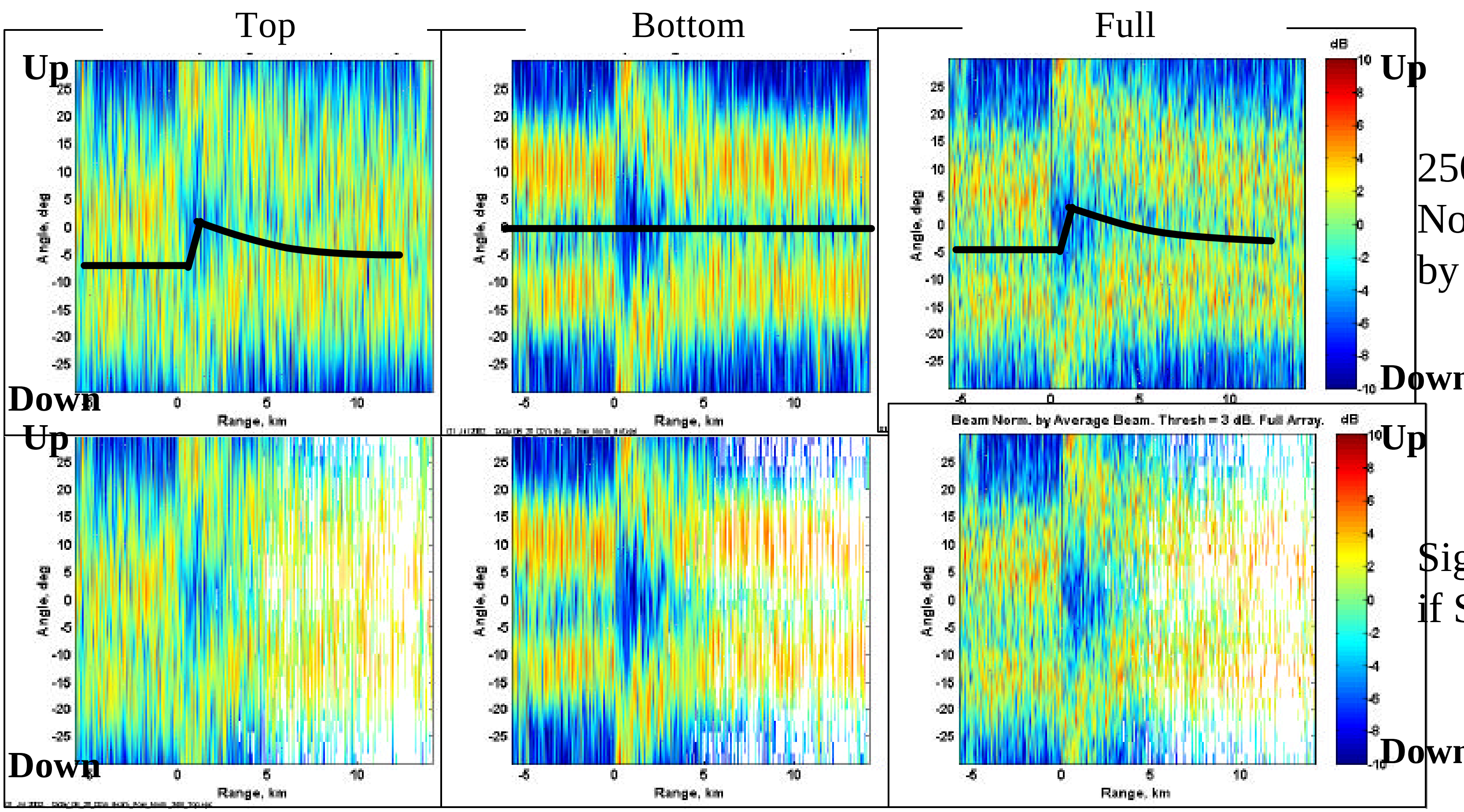
- Shot-to-shot stability:
- Look at all 4 shots provided.
  - Shallow sensor.
  - Common TL model
    - Linear TL
    - Range-independent src.
- Very similar results for 4 shots



- Observe same SS for shots 1-4.
- Potentially 2.5 dB uncertainty due to weight.
- Uncertainty in level and F-dependence.
  - Linear TL model results in
    - Higher SS above 200 Hz
    - F^3 frequency dependence of SS
    - SS increasing with R for R=4-10 km, F>240 Hz.
  - Nonlinear TL model results in
    - Lower SS above 200 Hz
    - $F^{2.5}$ frequency dependence of SS
    - SS independent of range for R=4-10 km.
- What is the correct TL model?
- Do we need to address non-linear source effects?
- Conclude:
  - dB-difference between L and NL models not huge - within 5dB.
  - But TL model affects F-dependence (important for understanding physics/mechanisms of bottom interaction)
  - It is important to settle on the correct TL model and determine correct F-dependence of the SS.

Array Processing

- VLA can be used to study dependence of bottom SS on the scattering angle.
- I focus on bottom subarray (middle column). Reasons:
  - Down refracting so to look at low grazing angles need to be close to bottom.
  - Remove contribution from surface, focus on bottom scattering contribution.
  - SNR is good to 5-10 km depending on steering angle and frequency band.



250 Hz octave
Normalized
by horizontal.

Signal clipped
if SNR≤3 dB

Angular Dependence of Scattering Strength: Procedure

- To determine bottom scattering strength SS(F,R, α_i, α_s), need to normalize beam output by
  - Source function
  - Insonified area
  - TL
- Incidence angle α_i:
  - Can not be controlled with explosive source.
  - Can only be determined from modeling.
  - May change as function of range due to stripping of high angles.
- Scattering angle α_s:
  - Can be related to steering angle.

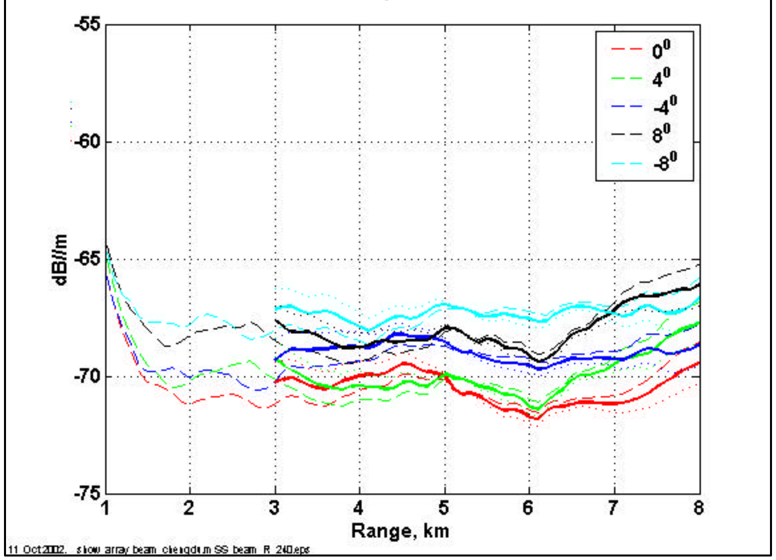
- Using different array beams, can obtain SS(F,R ,α_{i0},α_s)
  - α_{i0} is average incidence angle (fixed at each range).

- Caveat 1: As for single sensor, SS potentially depend on range due to scattering into different angles (coupling between modes).

- Caveat 2: SS may depend on range through TL dependent on angle (bounce loss). Need to use TL(f,R,θ_S), where θ_S is steering angle. Used single-phone TL(f,R) instead.

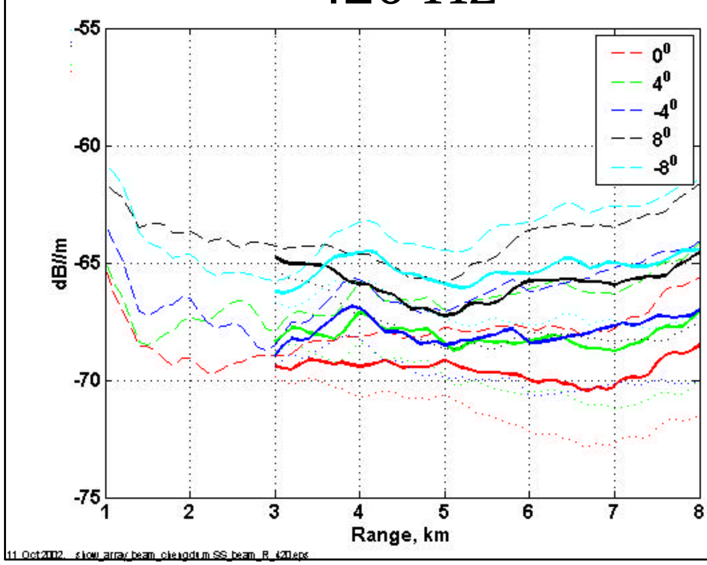
SS in Beam: Range Dependence

240 Hz

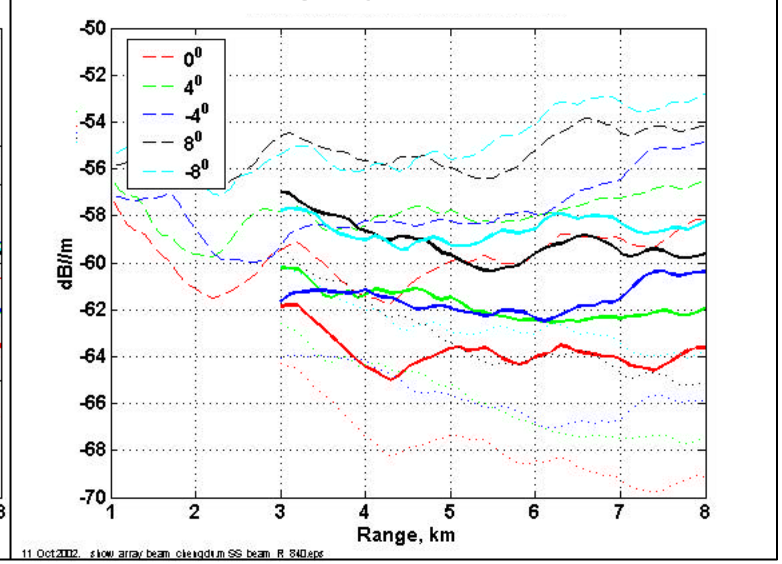


- As for sensor, have similar source-induced uncertainty.
  - Linear source: dash curves, upward rend
  - Nonlinear source: dotted curves, downward trend
  - Linear/Nonlinear combination: solid curves.

420 Hz

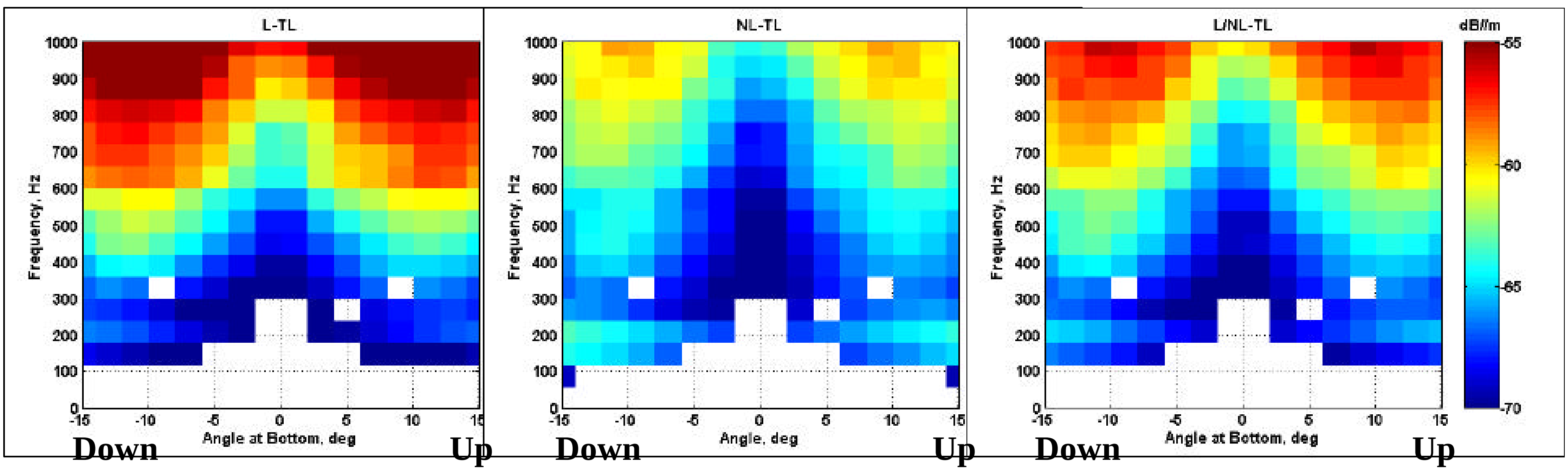


840 Hz



SS vs. Angle at Scatterer and Frequency

- $SS(\theta_G, f)$
  - f is frequency
  - θ_G is average array beam incidence angle at the bottom (average scattering angle).
- Notation:
  - Negative angles: results observed in down-steered beams.
  - Positive angles: results observed in up-steered beams.



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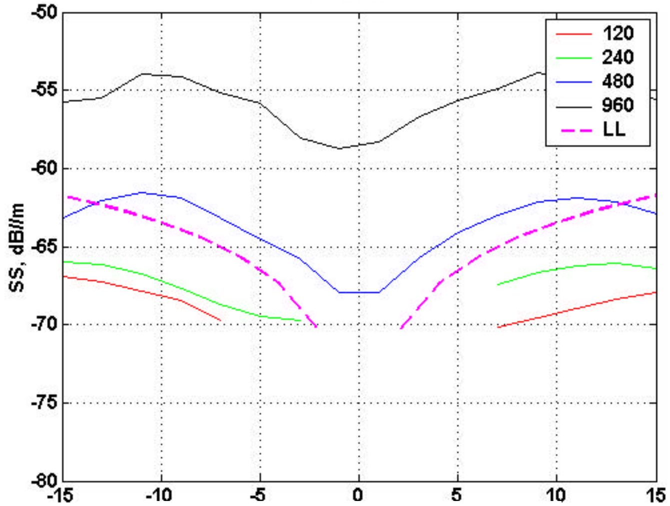
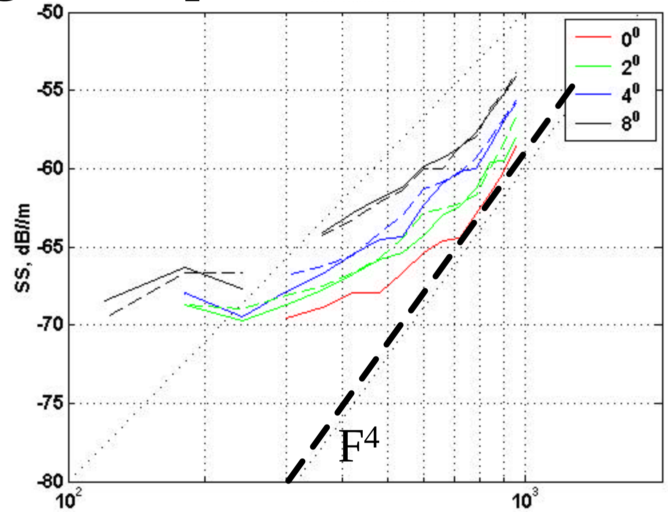
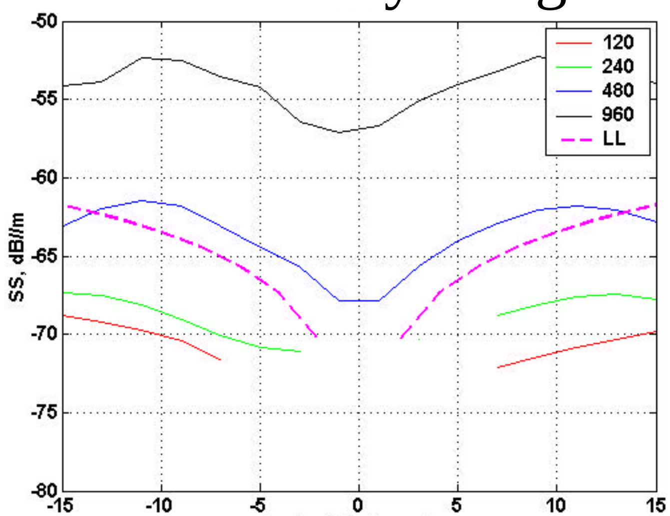
SS in Beam: Angular and Frequency Dependence

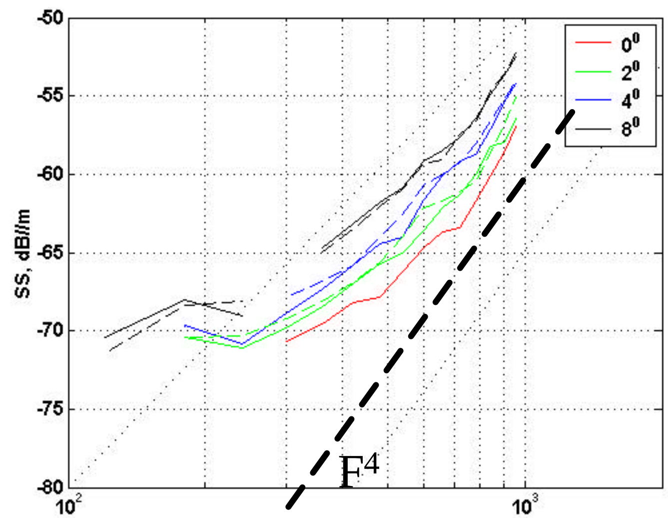
Base: Linear TL, Range-Independent Source





Try Range-Dependent Source





Angular dependence: surprisingly Lambertian

Very steep F-dependence:

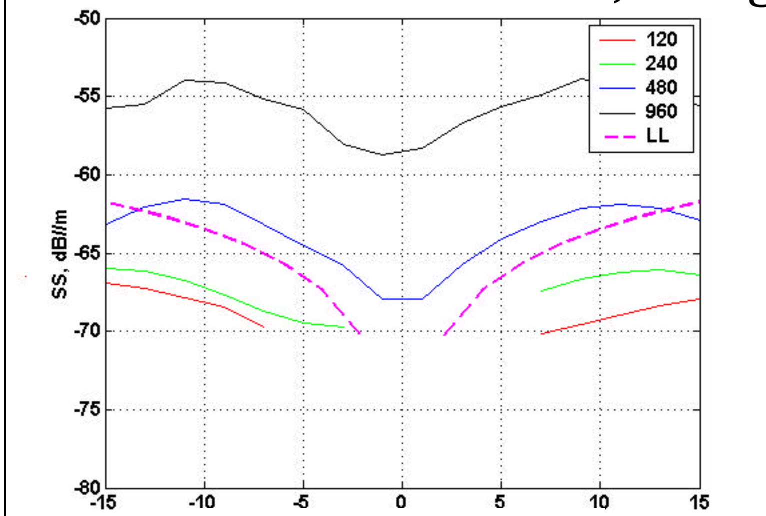
- In low beams, steeper than F^4

Error in SS extract?

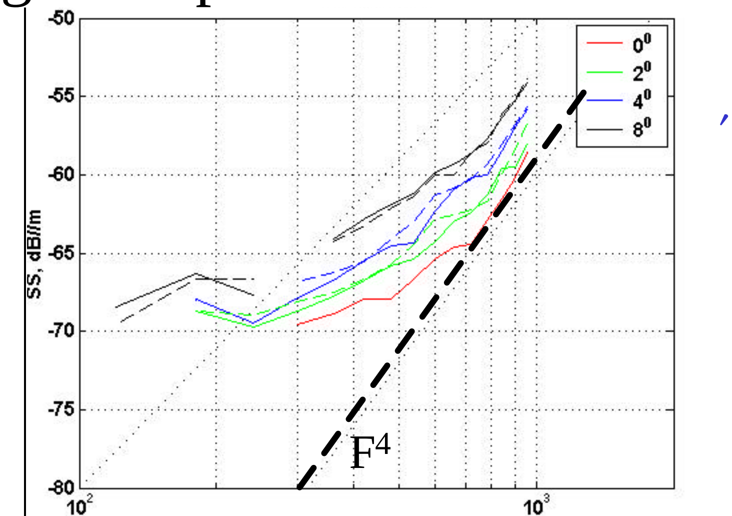
Or tells us about scattering mechanisms?

SS in Beam: Angular and Frequency Dependence

Base: Linear TL, Range-Independent Source



Angle at bottom, deg.



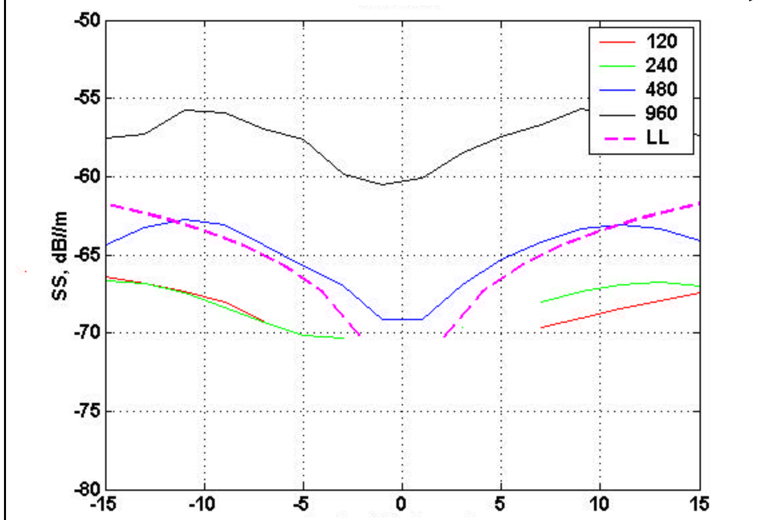
Frequency, Hz

Lambertian angular dependence.

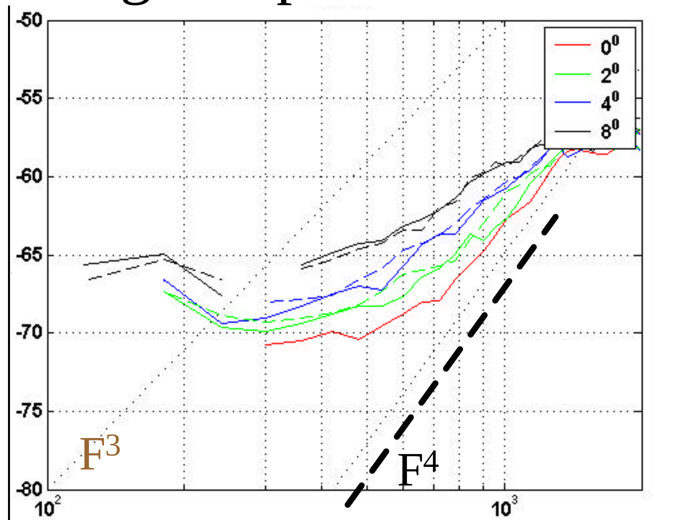
Steep F-dependence:

- F^4 in low beams – sub-bottom?
- Any errors in SS extract?
- F^4 or steeper?

Base: Linear/Nonlinear TL, Range-Dependent Source



Angle at bottom, deg.



Frequency, Hz

Questions/Issues

- Assuming non-linear source, can “straighten” range-dependence of SS in single sensor and in beam.
- Does this mean that we should account for source nonlinearity?
- May be, but may be not, as there are potential mechanisms for range dependence of the SS:
  - Range-dependence of environment
  - Scattering into different angles (coupling between modes) increasingly important with range
  - Angular dependence of TL for the VLA beam data.

Conclusions

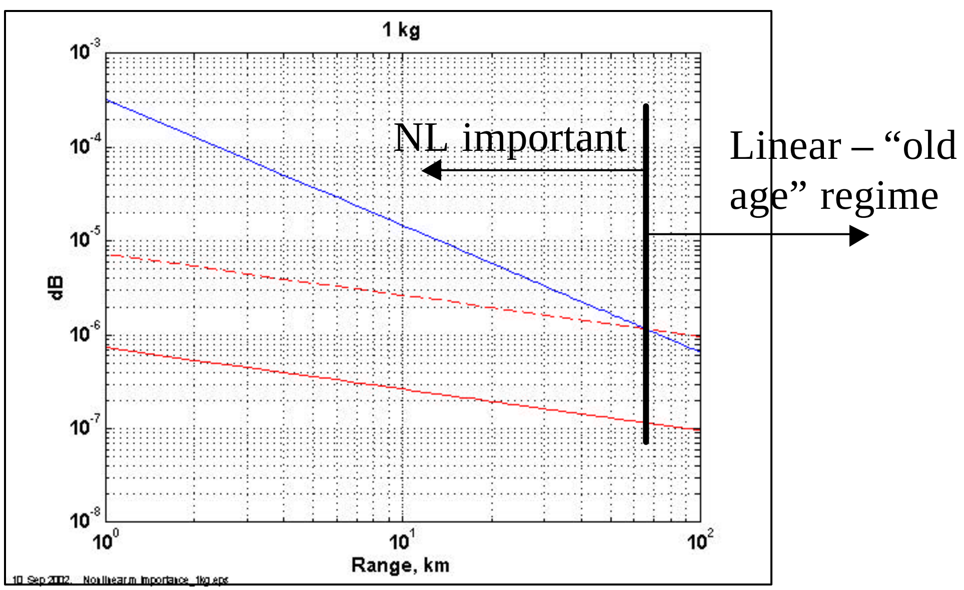
- Generally low bottom SS, increasing with frequency for f>400 Hz.
- Steep frequency dependence, steepening with decreasing of grazing scattering angle.
- At each frequency, angular dependence can be approximated by Lambert Law. Assuming 15^0 incidence angle (which is close to maximum propagating angle), need McKenzie coefficient of about –50 dB (at 120 Hz) to about –40 dB (at 840 Hz).
  - Low values of McKenzie coefficient.
  - Lambert Law provides functional fit but does not correctly describe the physics of scattering. Impossible to relate required values of McKenzie coefficient to environmental parameters.

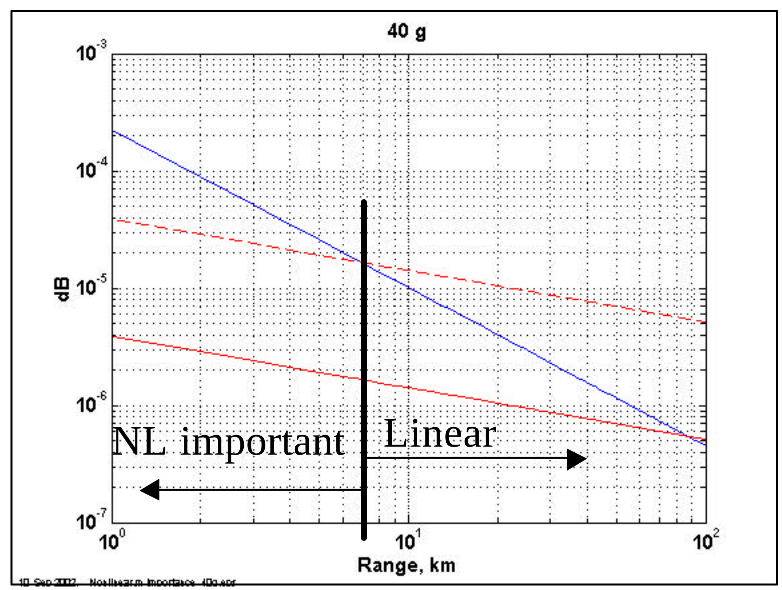
- Need to compare to physics-based theoretical predictions (e.g.: surface, sediment, volumetric, SP/Born).
  - F-dependence of SS is very important as it may suggest bottom interaction mechanisms
    - For example, F^4 can be argued due to scattering from small scatterers distributed near water/bottom interface (biologic activity?)
  - Current uncertainty in TL modeling does not result in large dB-difference in SS extractions, but affects frequency dependence.
  - Need to better understand empirical SS for better understanding of scattering mechanisms.

BACKUP

Importance of Nonlinear Effects

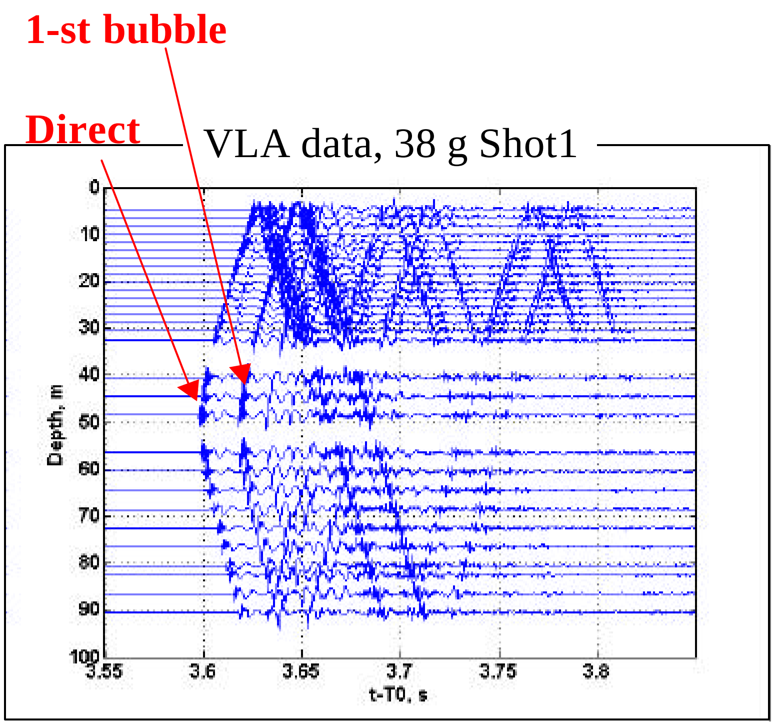
- Pierce , "Acoustics": Nonlinearity counts if $\beta \cdot P_0 \cdot 2\pi F_0/(\rho \cdot C^3) > \alpha$, where:
  - $\beta=3.5$ is parameter of nonlinearity.
  - P_0 and F_0 are pressure and frequency characteristic for the waveform.
  - α is linear attenuation (in nepers/m): $\alpha=10^{-3}/10\log10(e)$, where a is attenuation in dB/km.
- Use empirical expressions from Urick for a charge of W lbs at range R feet:
  - $P_0=C_0 \cdot 2.16 \cdot 10^4 \cdot (W^{1/3}/r\,)^{1.13}$ (Pa), where $C_0= (0.454 \cdot 9.8)/0.0254^2$;
  - $F_0=10^6/\tau$ - characteristic frequency, Hz, where $\tau=58 \cdot W^{1/3} \cdot (W^{1/3}/r)^{0.22}$ – characteristic duration, μs
- Use empirical curves for free water attenuation from Dyer:
  - $a=(3{:}30) \cdot 10^{-3} \cdot (F_0/1000)^2$ – attenuation, dB/km, for $T=4^0\text{-}22^0$ C (lower for higher temperature).
  - $\alpha=a \cdot 10^{-3}/10\log10(e)$.
- In reality, transition to linear happens earlier due to:
  - a and α are higher due to additional attenuation on boundary interaction.
  - P_0 and F_0 were computed with account to spherical spreading, but spreading may further slow steepening

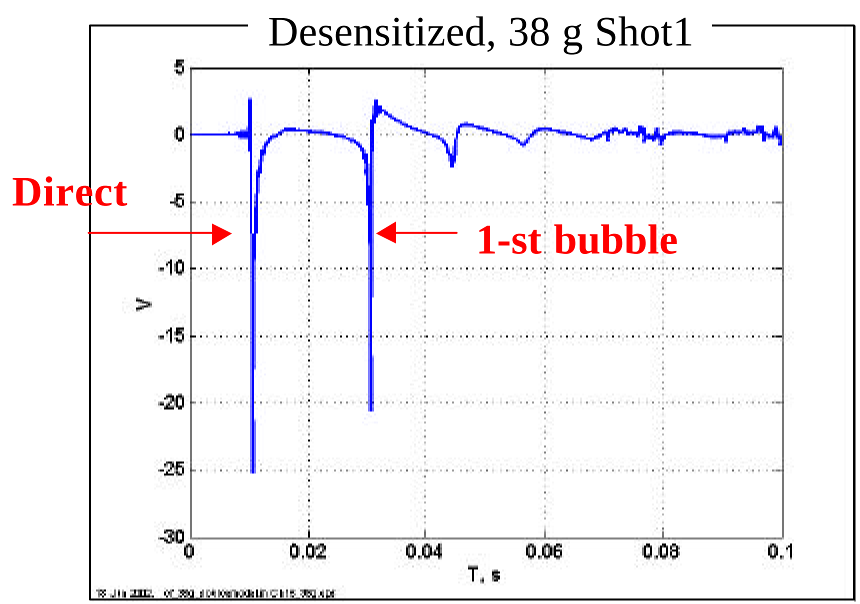




38 g Shot, Direct Arrival on VLA

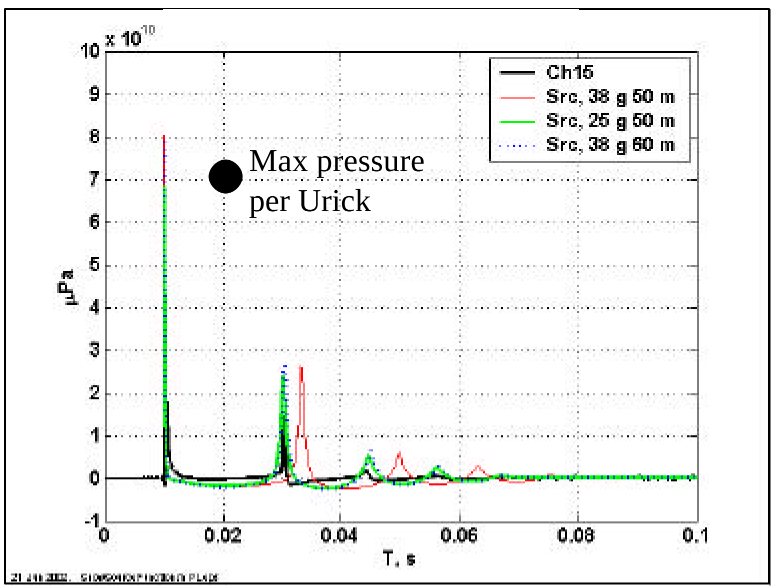
- Small source ground truth: 38 g detonated at 50 m.
- From data: detonation depth is about 52 m – from first arrival structure on VLA.
- On direct arrival all hydrophones (including desensitized) clipped but multipath and bubble pulse structure is clearly evident.
- Separation between pulses can be used to infer detonation strength.





38 g Shot, Direct Arrival on Desensitized Phone vs. Wakeley

- Below, data are compared to the Wakeley model.
- Levels between data and model can't be matched because of clipping.
- To fit the scale, source was placed at 100 m.
  - Black dot: P_{max}≈217 dB//μPa – peak level at 100 m per Urick. Shown for reference.
  - Black: data, desensitized hydrophone (clipped).
  - Red: 38 g source at 50 m depth, does not match pulse separation in data.
  - Green: 25 g source at 50 m, matches pulse separation.
  - Blue: 38 g source at 60 m, also matches pulse separation, but depth does not match that inverted from first arrival.



Conclude:

Actual detonation depth is about nominal.

Actual charge is 25 g – 34% less than nominal.